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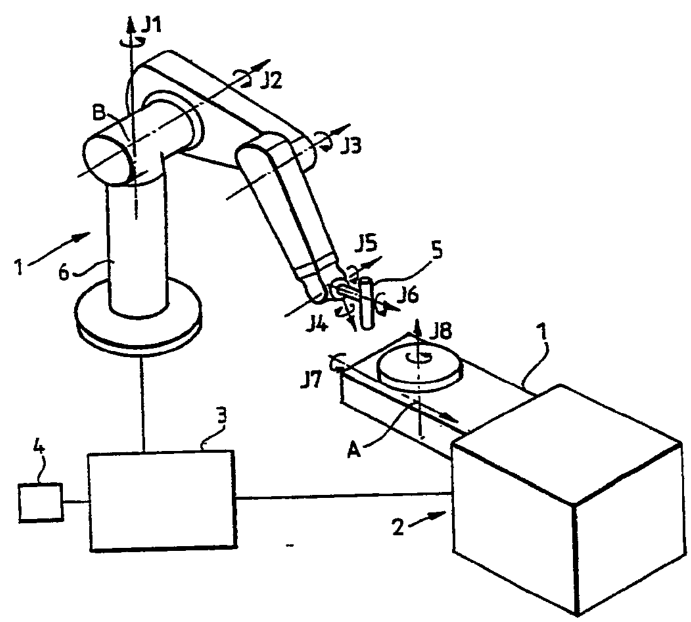
(54) Title: A METHOD FOR THE CONTROL OF THE PATH OF A ROBOT CELL



(57) Abstract

This invention relates to a method for the control of the path of a robot cell, comprising a robot (1) of at least five degrees of freedom, a workpiece manipulator (2) of at least two degrees of freedom, and a control unit (3) controlling synchronously the robot and the workpiece manipulator. To facilitate the teaching of synchronous movements of the robot and the workpiece manipulator and to optimize the orientation of the tool for the work process, the method of the invention comprises the steps of bringing the robot (1) and the manipulator (2) by a manual control (4) to a desired position with respect to each other at points essential for the path; storing data concerning the orientation of the robot (1) and the manipulator (2) with respect to each other at said points in the control unit (3); applying path optimization criteria to the control unit (3); and calculating the optimal path on the basis of the optimization criteria and the data concerning the orientation of the robot and the manipulator with respect to each other by means of the control unit.

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A method for the control of the path of a robot cell

This invention relates to a method for the control of the path of a robot cell comprising a robot of at least five degrees of freedom, a work-piece manipulator of at least two degrees of freedom and a control unit controlling synchronously the robot and the workpiece manipulator, in which method the robot and the manipulator are brought to a desired position with respect to each other by a manual control at points essential for the path; and data concerning the orientation of the robot and the manipulator with respect to each other at said points is stored in the control unit.

There are robot systems in which the movements of the robot and the workpiece manipulator, usually a rotary table, can be controlled synchronously to achieve controlled path movement relative to a work-piece positioned on the rotary table (e.g., a linear movement). The systems enable complicated paths as compared with systems with no synchronization. During welding, for instance, the axes of the rotary table cannot be turned in asynchronous systems because otherwise the path of the tool could not be controlled (a straight movement, for instance, is not straight relative to the workpiece positioned on the rotary table). In prior art synchronized systems the robot and the rotary table drive through points they have learned at the teaching step. As a result, when the operator teaches synchronized paths, he first has to turn the workpiece into a position advantageous for the work process and then teach the point by means of the robot. When driving along the taught path, the axes of the rotary table turn linearly from the initial position to the final position, during

which time the robot is adopted to the movement of the table to achieve a desired path. One problem is that the orientation of the tool does not necessarily stay optimal for the work process. Even though the initial and final points of the welding path would have been taught in a so-called downhand position, the synchronized movement may cause the welding burner to be displaced away from the downhand position at some points along the path.

The object of the present invention is to provide a method for the control of the path of a robot cell without the above-mentioned problems associated with, e.g., the control of the orientation of the tool in synchronized movements. The object of the invention is thus to provide a robot cell to which synchronized movements can be taught rapidly and in which the optimal orientation of the tool in view of the work process can be achieved more easily. This is achieved by means of a method of the invention which is characterized in that it further comprises the steps of

- applying path optimization criteria to the control unit; and
- calculating the optimal path on the basis of the optimization criteria and the data concerning the orientation of the robot and the manipulator with respect to each other by means of the control unit.

In the method of the invention the position and orientations of the robot and the workpiece manipulator relative to the surroundings can be selected so as to enable easiest possible teaching. Essential is that the orientation of the tool gripper and workpiece manipulator of the robot with respect to each other at the teaching step is the right position for carrying out the work. In addition to the desired

points of the path it is this orientation that is stored in the memory. On the basis of this orientation and the optimization criterion applied to the control unit, concerning, e.g., the orientation of the welding burner during the welding process, the central unit is then able to calculate the final optimal path to be used during the actual performance of the work. In this way the teaching step can be made more rapid and simpler and nevertheless obtain a path in which the orientation of the tool and the workpiece with respect to each other as well as their orientation with respect to the surroundings are optimal for the performance of the work.

The orientation of the robot and the workpiece manipulator with respect to each other is preferably stored as the position of the coordinate system of the tool gripper of the robot with respect to the coordinate system of the base of the robot and as the angle positions of the joints of the workpiece manipulator. The method is even simpler in that the robot and the workpiece manipulator can be brought to a desired orientation with respect to each other merely by controlling the robot while the orientation of the manipulator remains unchanged.

In the following the method of the invention will be described in more detail with reference to the attached drawings, in which

Figure 1 is a schematic view of a robot cell assembly of the invention;

Figure 2 shows the positions of the joints of the robot cell of Figure 1 and the respective coordinate systems; and

Figure 3 shows a control system included in the robot cell of Figure 1 in the form of a block diagram.

The method of the invention requires that the robot cell is formed by a robot 1 of at least five degrees of freedom, a rotary table 2 of at least two degrees of freedom; and a control unit 3 controlling the robot and the table. The control unit 3 is able to drive both the robot 1 and the rotary table 2 simultaneously. A workpiece (not shown) is attached to the rotary table 2 and a required tool (not shown) to the robot 1. Main robot joints J1, J2, J3 may be either rotary joints or linear joints. Wrist joints J4, J5, J6 have to be rotary in order that the control unit 3 could change the orientation of the tool if required. Joints J7, J8 have to be rotary-type in order that the control unit 3 could change the orientation of the workpiece relative to the robot.

A rectangular coordinate system T is positioned at the intersection of the axes of the rotary table, a rectangular coordinate system W at the fastening base of the robot, and a rectangular coordinate system P at the tip of the tool. The orientation of the coordinate system T is determined by the joint angles of the axes of the rotary table. When teaching the points of the path the position of the coordinate system relative to the coordinate system W or T at each point P and the joint angles J7, J8 of the rotary table are stored in the memory of the control unit for each point.

When performing synchronized movements, the path calculation is effected relative to the coordinate system T in place of the coordinate system W. The control unit 3 performs the necessary transformations from the coordinate system W to the coordinate system T and vice versa. To optimize the path, the control unit 3 drives the joints of the rotary table in such a way that the z axis of the

tool has a constant predetermined orientation relative to the coordinate system W during the movement (in welding, for instance, it is preferable that the z axis of the coordinate system of the tool points downward, a so-called down-hand position). During each calculation period, the control unit calculates

- a new path point Pi relative to the coordinate system T;
- such values for the joint angles J7, J8 of the rotary table 2 that the point Pi positioned within the coordinate system T turns into an optimal position (point Pi2);
- the position of the point Pi2 relative to the coordinate system W (point Pi3);
- the joint angles J1...J6 on the basis of the value of the point Pi3;
- positional values for encoders E1...E8 corresponding to the angles J1...J8; and
- commands each joint servo NS1...NS8 to drive to the calculated encoder value.

Since the optimization is carried out during each calculation period, it is possible to teach the path points in a non-optimal position while retaining the optimal position throughout the path when repeating the taught path.

Figure 1 shows a system by means of which the path optimization of the invention can be realized. The robot is a joint mechanism of six degrees of freedom in which all the joints are rotary joints. The rotation axes of the joints are indicated J1, J2...J6. The rotary table 2 comprises two rotary joints the axes of which are indicated J7 (turning) and J8 (rotation). The axes of the rotary table are perpendicular to each other and intersect at a point

A. The axis J8 is parallel with the x axis of the coordinate system W. Each joint comprises a motor M1...M8 which can be driven through a respective joint servo NS1...NS8. To read the position of the joint, the motors comprise absolute encoders E1...E8, from which signals are applied to the corresponding joint servos NS1...NS8. The workpiece is fixed to the rotary table 2, and the tool is fixed to the tool flange of the robot. The cell can be used, for instance, for welding workpieces if the robot is provided with a welding equipment.

Figure 2 shows a reduced model of the system of Figure 1. The direction of the coordinate system W of the robot is selected so that the direction of the z axis is the direction of the joint J1, the direction of the y axis is the direction of J2 when the joint angle J1 is 0, and the x axis is perpendicular to said axes. The origin of the coordinate system W is at the intersection B of the axes J1 and J2. The z axis of the coordinate system T of the rotary table points in the direction J8 (= the direction J1) and the x-axis in the direction of the x axis of the coordinate system W when J7 and J8 are at an angle of 0. The origin of the coordinate system T is positioned at the intersection A of the axes of J7 and J8. The position and orientation of the coordinate system P of the tool relative to the coordinate system W depend on the joint angles J1...J6 of the robot; the origin of the coordinate system of the tool is positioned at the tip of the tool.

Figure 3 shows the control system of the cell. The joint servos NS1...NS8 are connected to the corresponding motors M1...M8 of the robot 1 and the rotary table 2 and to the encoders E1...E8. Each joint servo is able to control its joint in response

to instructions received from the control unit 3. The control unit may, e.g., instruct the joint servo to drive up to a desired encoder reading. When teaching the robot to drive from one point to another, the taught points are stored in the memory 7 of the control unit 3. At each point the position of the coordinate system P relative to the coordinate system W and the joint angles J7 and J8 of the rotary table are stored. The function of a calculation unit 8 included in the control unit 3 is to calculate the interpolation points of the paths in the coordinate system of the rotary table, to perform the change of orientation to a desired optimal position by means of the rotary table, to transform the optimized point to the coordinate system W, to calculate the joint angles J1...J6 corresponding to the position of the point (the values of J7, J8 are calculated at the optimization step), and to lead the joint servos to the calculated position. To achieve sufficient path accuracy, the interpolative calculation interval has to be a few milliseconds.

During the teaching step the operator may keep the position of the rotary table unchanged. The teaching of the point takes place by driving the robot 1 by means of a manual control 4 to a desired point in a desired orientation with respect to the workpiece. The position and orientation of the point as well as the joint angles of the rotary table are stored in the memory. The position and orientation of the point can be stored with respect to the coordinate system W, the coordinate system T, or as the robot joint angles. The joint angles J7, J8 of the rotary table at the teaching moment are stored in the memory. In this way all the required points of the path are taught.

When repeating the taught path (e.g., a linear path from the point P1 to the point P2), the calculation unit 8 has to transform the points P1 and P2 from the coordinate system W to the coordinate system T. The point stored in the memory can be presented in the form of the transformation matrix

$$Pw = \begin{pmatrix} nx & ox & ax & px \\ ny & oy & ay & py \\ nz & oz & az & pz \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

where vector {px,py,pz} = position of the origin of the point

vector {nx,ny,nz} = the x axis of the coordinate system of the tool at the point Pw

vector{ox,oy,oz} = the y axis of the coordinate system of the tool at the point Pw

vector {ax,ay,az) = the z axis of the coordinate system of the tool at the point Pw

The transformation of the point Pw from the coordinate system W to the coordinate system T takes place by multiplying the point Pw in the coordinate system W by the inverse matrix T' of the transformation matrix T describing the position and orientation of the coordinate system T

$$Pt = T'*Pw$$

The matrix T is easy to determine when the po-

sition of the origin of the coordinate system T in the coordinate system W and the joint angles J7, J8 of the axes of the rotary table are known

$$T = \begin{pmatrix} C8 & -S8 & 0 & px \\ C7*S8 & C7*C8 & -S7 & py \\ S7*S8 & S7*C8 & C7 & pz \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

where C7 = cos(J7)
C8 = cos(J8)
S7 = sin(J7)
S8 = sin(J8)
vector {px,py,pz} = position of the origin of the coordinate system T in the coordinate system W

When the points P1 and P2 of the path are known in the coordinate system T, the interpolative calculation of the path can be performed with respect to the coordinate system T. A corrected value is calculated for each interpolation point Pti of the path to realize optimal orientation. The workpiece is brought into optimal orientation in the following way:

The vector T*Pti z is calculated

$$T*Pti = \begin{pmatrix} \ldots & \ldots & C8*ax - S8*ay & \ldots \\ \ldots & \ldots & C7*S8*ax + C7*C8*ay - S7*az & \ldots \\ \ldots & \ldots & S7*S8*ax + S7*C8*ay + C7*az & \ldots \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

The vector T*Pti z is marked to be equal to the desired optimal orientation v, thus obtaining a condition

vx = C8*ax - S8*ay
vy = C7*S8ax + C7*C8*ay - S7*az
vx = S7*S8*ax + S7*C8*ay + C7*az

where the unit vector {vx,vy,vz} = the desired optimal orientation.

The optimal values of J7 and J8 can be solved from this equation group when remembering that C7 = cos(J7) and C8 = cos(J8).

The interpolation point Pti is transformed from the coordinate system T to the coordinate system W in the following way

Pwi = To*Pti
Pwi = optimized point of the path in the co-ordinate system W
To = transformation matrix of the coordinate system T in the optimized orientation
Pti = path point with respect to the coordinate system T

On the basis of the point Pwi the joint angles J1...J6 of the robot can be calculated at the optimal point. The control unit 3 converts the joint angles into positional data for the encoders E1...E8 and drives the joints into the position in question by means of the joint servos NS1...NS8.

The method of the invention has been described above merely by means of one exemplifying embodiment, which relates to a welding application of the invention. It is to be understood that the method of the invention can also be applied in other robot cell applications in which either the robot or the work-piece manipulator are to be given either optimization or edge conditions. Such edge conditions may concern

the orientation of the robot or the workpiece manipulator, possible obstacles along their paths, restrictions in the range of movement of some joints, etc.

Claims:

1. A method for the control of the path of a robot cell, comprising a robot (1) of at least five degrees of freedom, a workpiece manipulator (2) of at least two degrees of freedom, and a control unit (3) controlling synchronously the robot and the workpiece manipulator, in which method the robot (1) and the manipulator (2) are brought to a desired position with respect to each other by a manual control (4) at points essential for the path; and data concerning the orientation of the robot (1) and the manipulator (2) with respect to each other at said points is stored in the control unit (3); characterized in that the method further comprises the steps of

- applying path optimization criteria to the control unit (3); and

- calculating the optimal path on the basis of the optimization criteria and the data concerning the orientation of the robot and the manipulator with respect to each other by means of the control unit (3).

2. A method according to claim 1, characterized in that the orientation of the robot (1) and the manipulator (2) with respect to each other is stored as the position of a coordinate system P of a tool gripper (5) of the robot (1) with respect to a coordinate system (W) of a base (6) of the robot (1) and as the angle positions of manipulator joints (J7, J8).

3. A method according to claim 1, characterized in that the optimization criterion comprises the orientation of the robot (1) or the manipulator (2) with respect to the surroundings.

4. A method according to claim 1, c h a r a c - t e r i z e d in that the robot (1) and the manipulator (2) are brought to a desired orientation with respect to each other by controlling the robot (1) while the position of the manipulator remains unchanged.

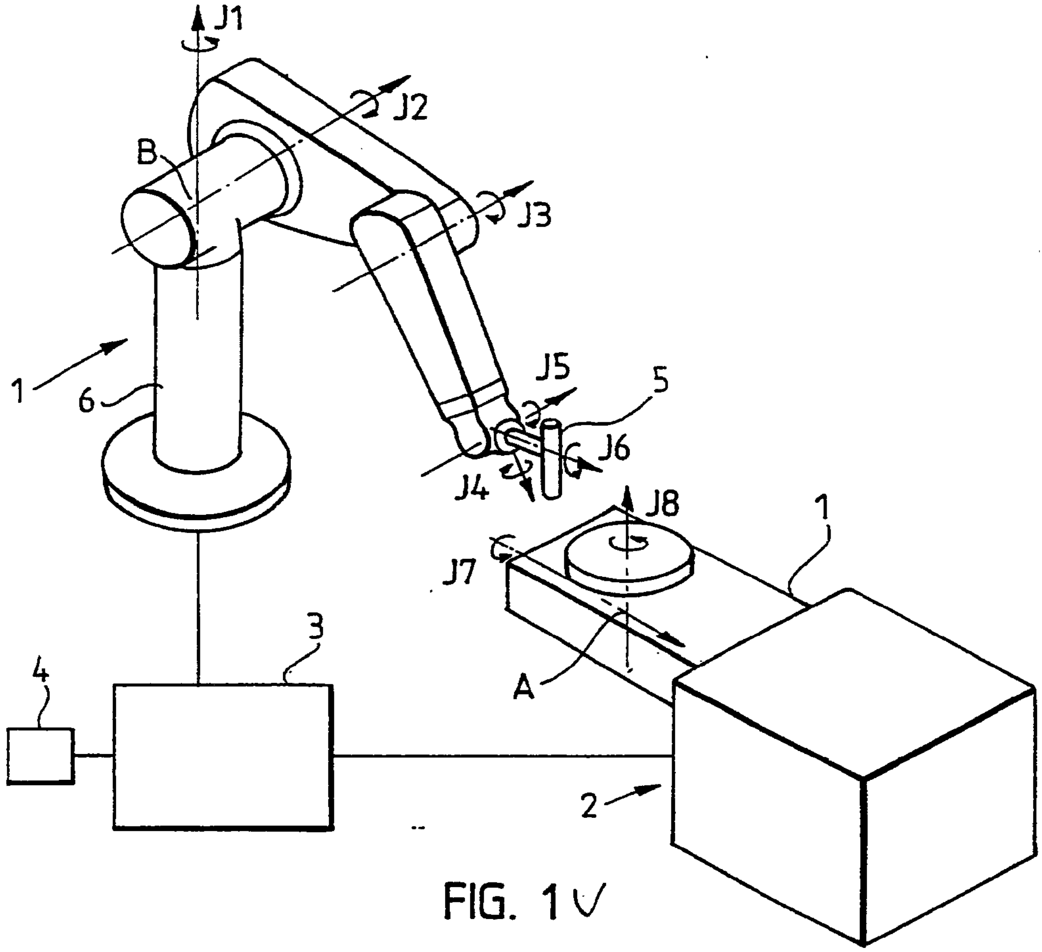
J1
J2
B
J3
1
6
J5
5
J6
J4
J8
1
J7
3
4
A
2

FIG. 1

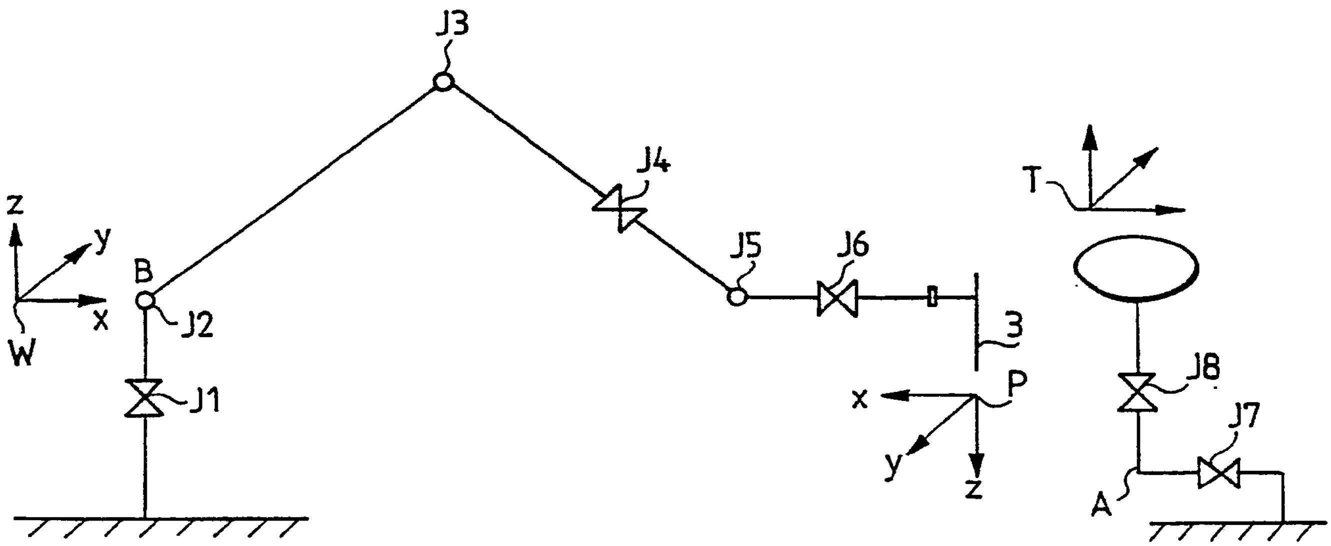
J3
J4
T
z
y
B
x
W
J2
J1
J5
J6
3
P
x
y
z
J8
J7
A

FIG. 2

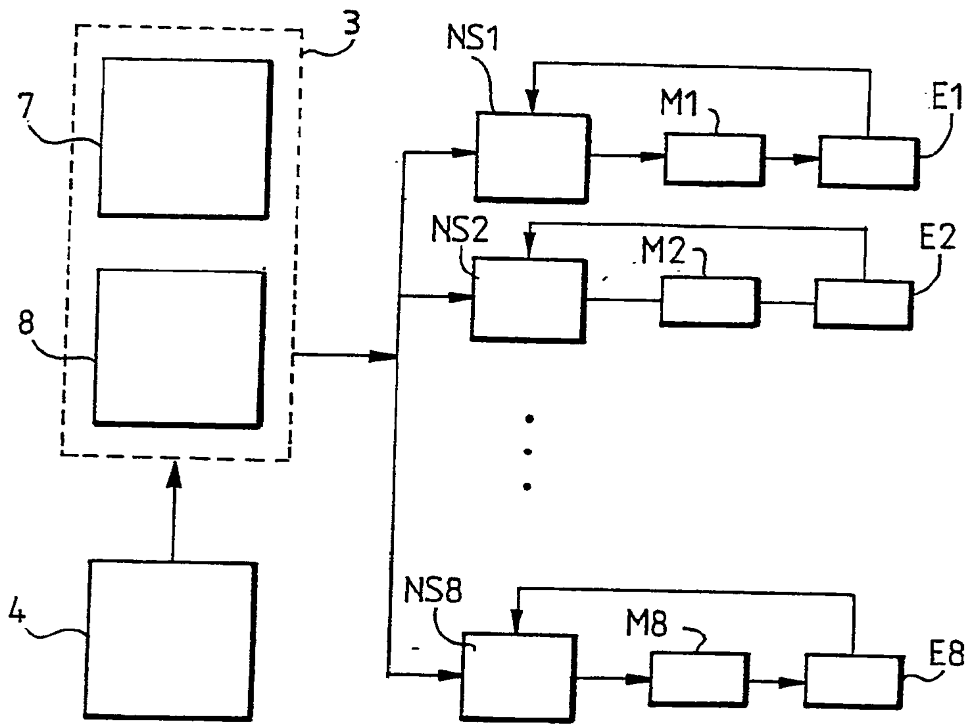

FIG. 3

INTERNATIONAL SEARCH REPORT

International Application No PCT/FI 90/00190

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all)[6]

According to International Patent Classification (IPC) or to both National Classification and IPC

IPC5: G 05 B 19/417, B 25 J 9/16

II. FIELDS SEARCHED

Minimum Documentation Searched[7]

Classification System	Classification Symbols
IPC5	G 05 B, B 25 J

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in Fields Searched[8]

SE,DK,FI,NO classes as above

III. DOCUMENTS CONSIDERED TO BE RELEVANT[9]

Category *	Citation of Document,[11] with indication, where appropriate, of the relevant passages [12]	Relevant to Claim No.[13]
A	WO, A, 8905486 (FANUL) 15 June 1989, see abstract --	1-4
A	EP, A, 177142 (CINCINNATI MILACRON) 9 April 1986, see abstract --	1-4
A	EP, A, 271691 (SIEMENS) 22 June 1988, see abstract --	1-4
A	US, A, 4836742 (TOYOTA) 6 June 1989, see abstract --	1-4
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IV. CERTIFICATION

Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report
20th December 1990	1991 -01- 02
International Searching Authority	**Signature of Authorized Officer**
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ANNEX TO THE INTERNATIONAL SEARCH REPORT ON INTERNATIONAL PATENT APPLICATION NO.PCT/FI 90/00190

This annex lists the patent family members relating to the patent documents cited in the above-mentioned international search report.
The members are as contained in the Swedish Patent Office EDP file on 90-11-28
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Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO-A- 8905486	89-06-15	JP-A- 1149113	89-06-12
EP-A- 177142	86-04-09	NONE	
EP-A- 271691	88-06-22	NONE	
US-A- 4836742	89-06-06	EP-A-B- 0158447 JP-A- 60193016	85-10-16 85-10-01